

Growing Food for Space and Earth:

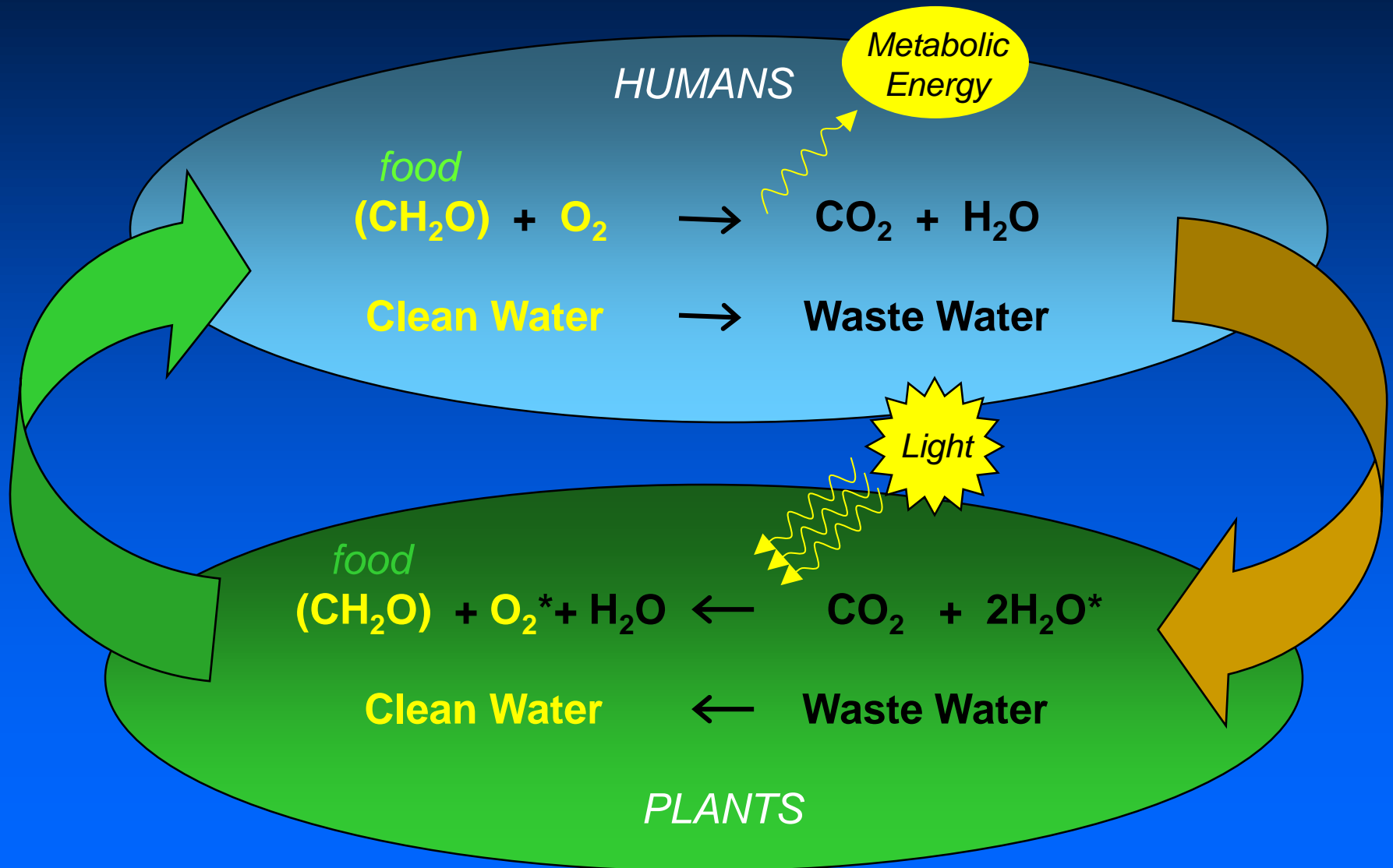
NASA's Contributions to Vertical Agriculture

Raymond M. Wheeler

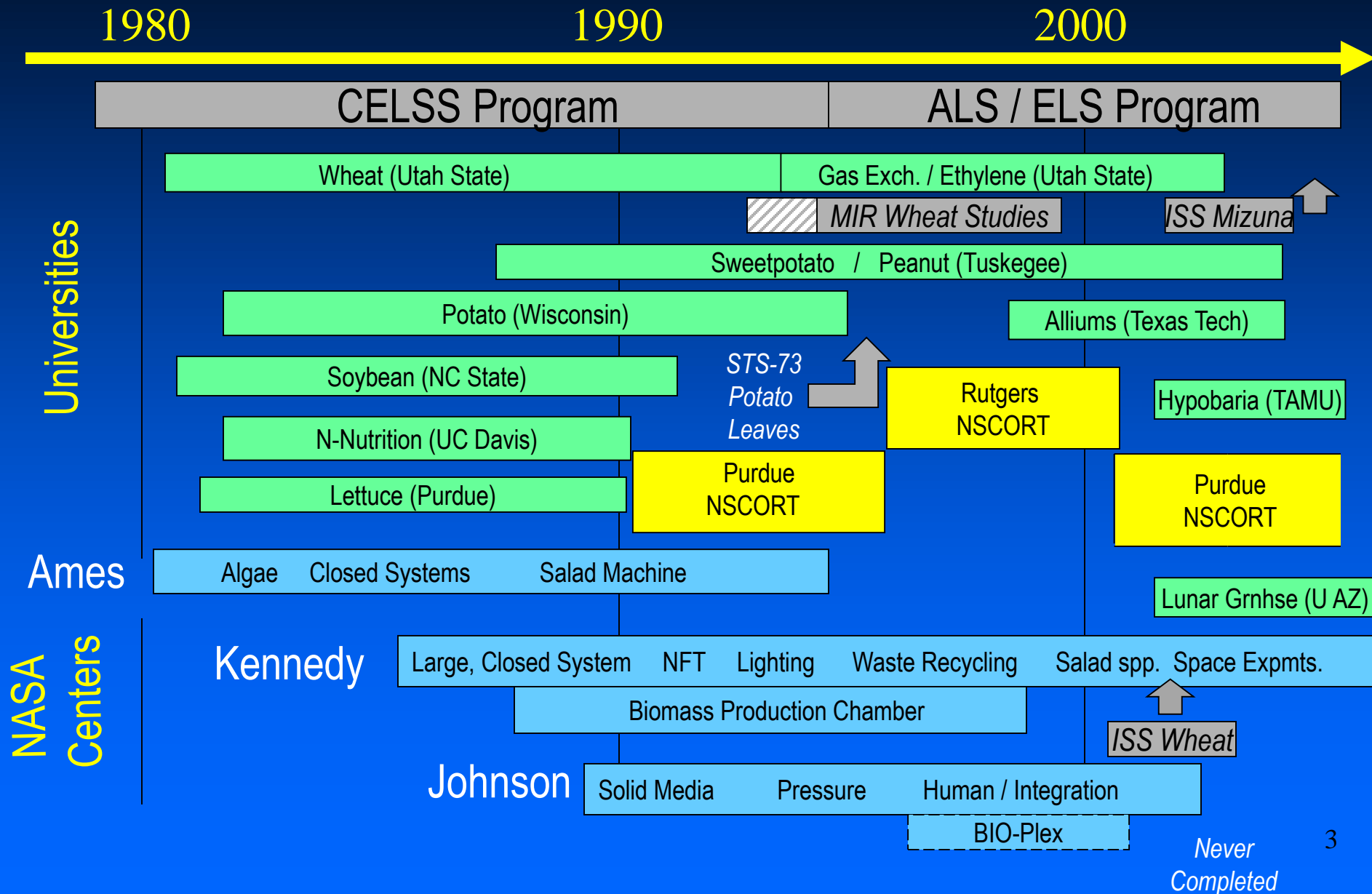
*NASA Exploration Research and Technology Directorate
Kennedy Space Center, Florida, USA*

**American Society of Horticultural Science
Aug. 4-7, 2015**

Plants for “Bioregenerative” Life Support



NASA's Bioregenerative Life Support Testing



Crop Considerations for Space

- High yielding and nutritious (CHO, protein, fat)
- High harvest index (edible / total biomass)
- Horticultural considerations
 - planting, watering, harvesting, pollination, propagation
- Environmental considerations
 - lighting, temperature, mineral nutrition, CO₂
- Processing requirements
- Dwarf or low growing types

Recirculating Hydroponics with Crops



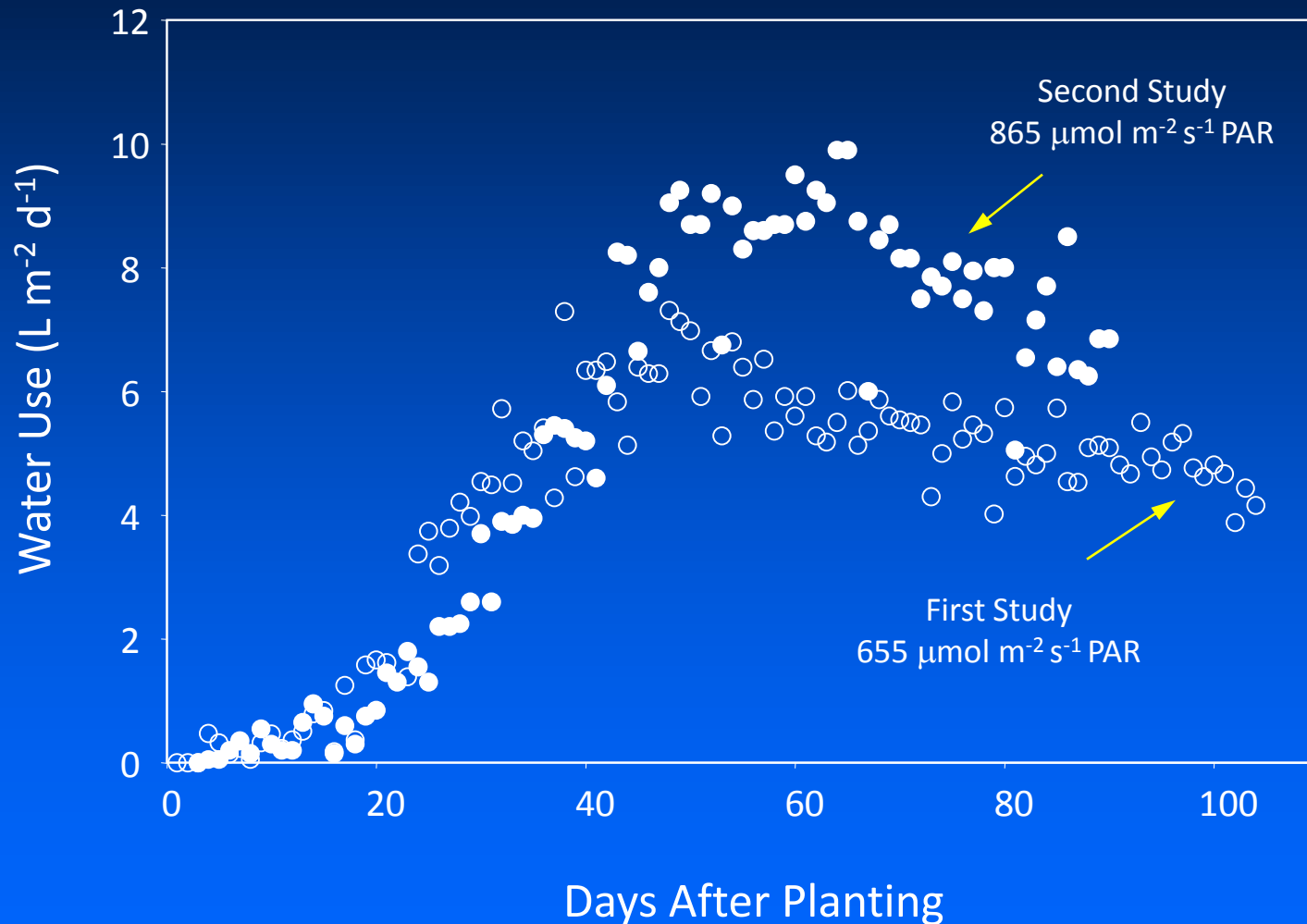
*Conserve Water & Nutrients
Eliminate Water Stress
Optimize Mineral Nutrition
Facilitate Harvesting*

Root Zone Crops in Nutrient Film Technique (NFT)

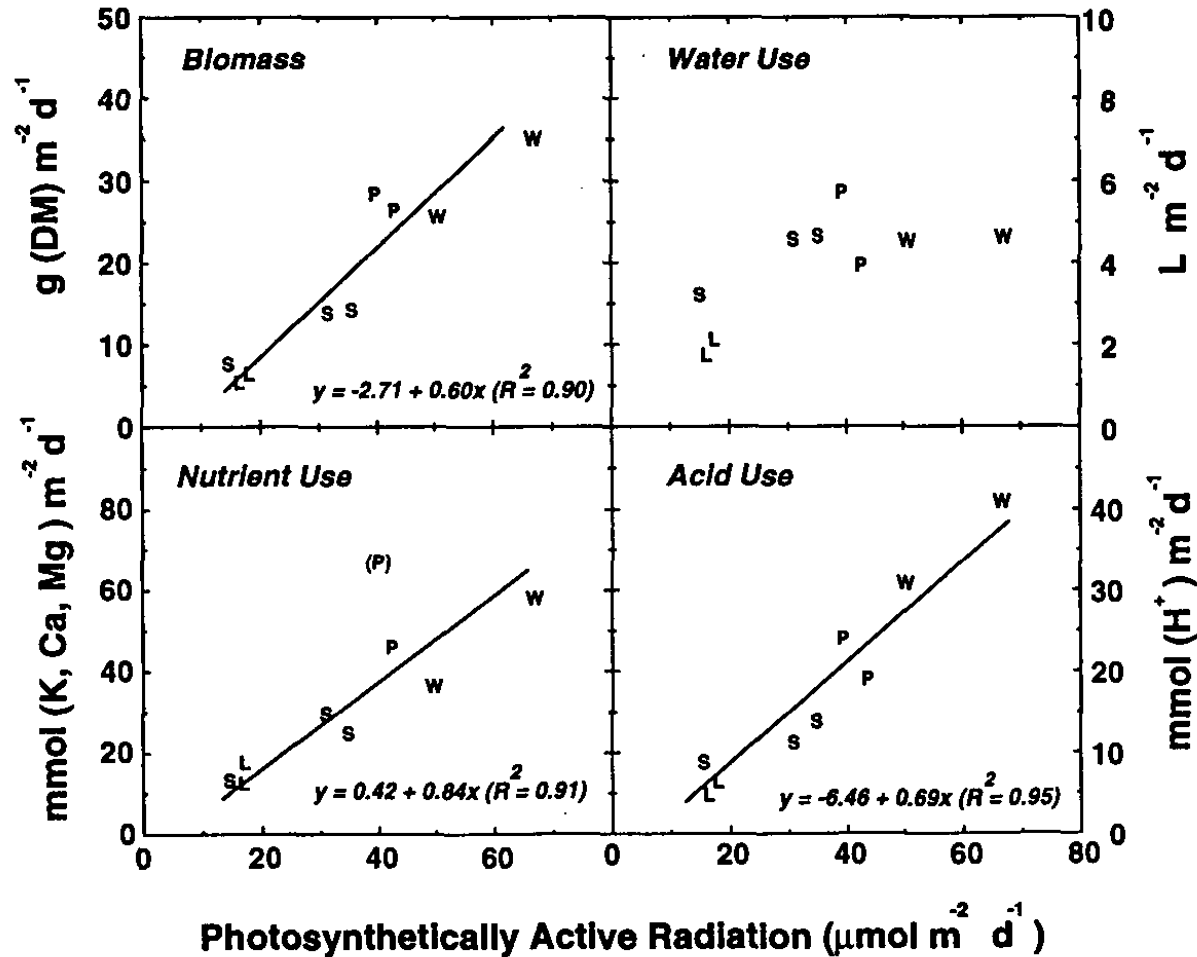


Fig. 7

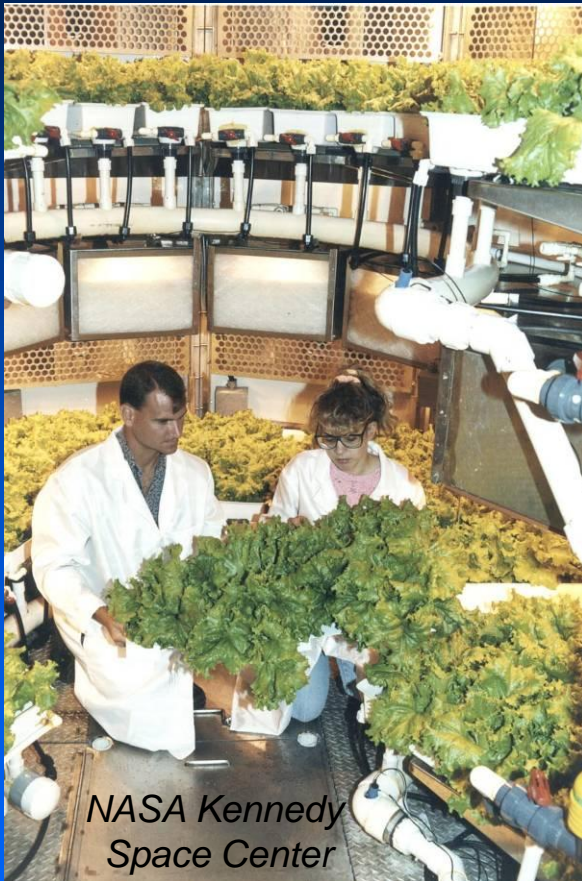
Evapotranspiration from Plant Stand (potato)



Water, Nutrient, and pH Control



High Yields from High Light and CO₂ Enrichment

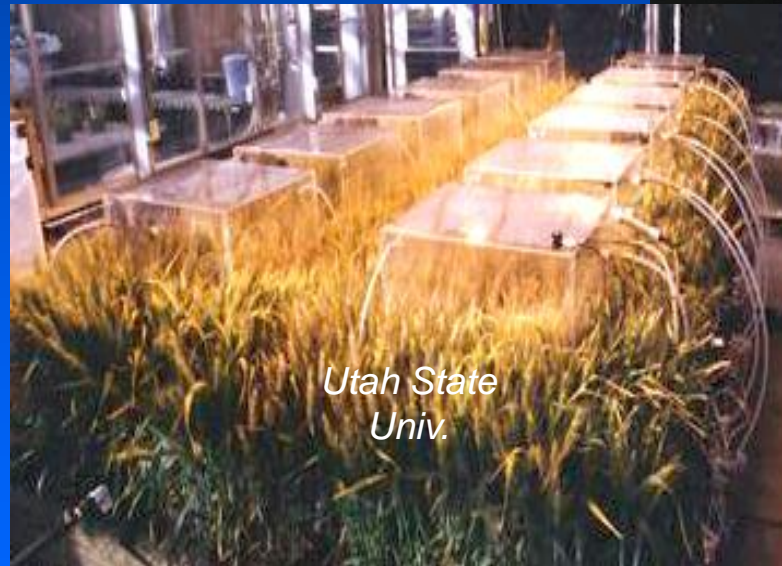


NASA Kennedy
Space Center

*Wheat - 3-4 x World Record
Potato - 2 x World Record
Lettuce-Exceeded Commercial
Yield Models*



Wisconsin Biotron



Utah State
Univ.

Bubgee, B.G. and F.B. Salisbury. 1988. Plant Physiol. 88:869-878.

Wheeler, R.M., T.W. Tibbitts, A.H. Fitzpatrick. 1991. Crop Science 31:1209-1213.

Potential Energy Conversion to Biomass

From Loomis and Williams. 1963. Crop Science 3:67-72

Assuming a maximum 12% conversion efficiency from PAR to biomass¹

1.6 g dry mass / mol PAR

¹ Radmer and Kok. 1977. BioScience. Actual instantaneous conversion efficiencies of ~10% reported from some controlled environment studies ; e.g., Wheeler et al., 1993. Crop Sci.; Gerbaud et al., 1998. Physiol. Plant.

Some Upper Limits to Energy Conversion and Productivity

Field Crops Observations¹

Crop	Productivity	Photosynthetic Energy Conversion Efficiency ²
	(g DM m ⁻² d ⁻¹)	(%)
Tall Fescue	43	7.0 (UK)
Maize	40	6.8 (US)
Sudan Grass	52	6.0 (US)

CEA NASA Studies

Crop	Productivity	Radiation Use Efficiency
	(g DM m ⁻² d ⁻¹)	(g DM mol ⁻¹ PAR)
Wheat	61	1.44 Utah State ³
	130	0.67 Utah State ⁴
Potato (12⇒24 h photoper.)	45	0.97 Univ. Wisc. ⁵
(12 h photoper. only)	38	1.15 Univ. Wisc. ⁵

¹ D.O. Hall. 1976. *FEBS Letters*

² Original data based on total solar irradiance; table data reflect efficiency based on PAR (400-700 nm)

³ Monje and Bugbee. 1998. *Plant Cell Environ* (estimated)

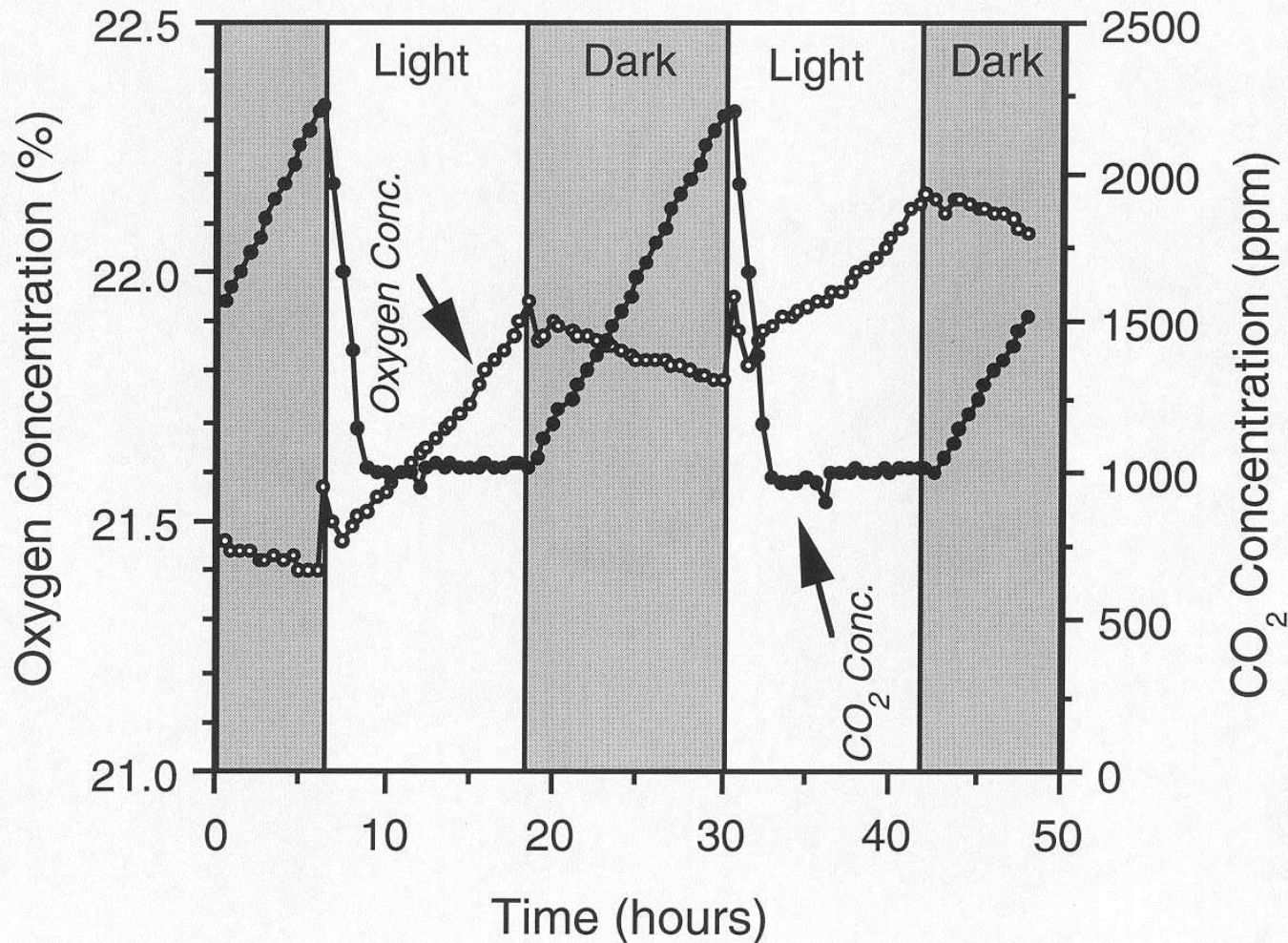
⁴ Bugbee and Salisbury. 1988. *Plant Physiol.*

⁵ From Wheeler, 2006. *Potato Res.* (assumes transplanting to increase PAR absorption).

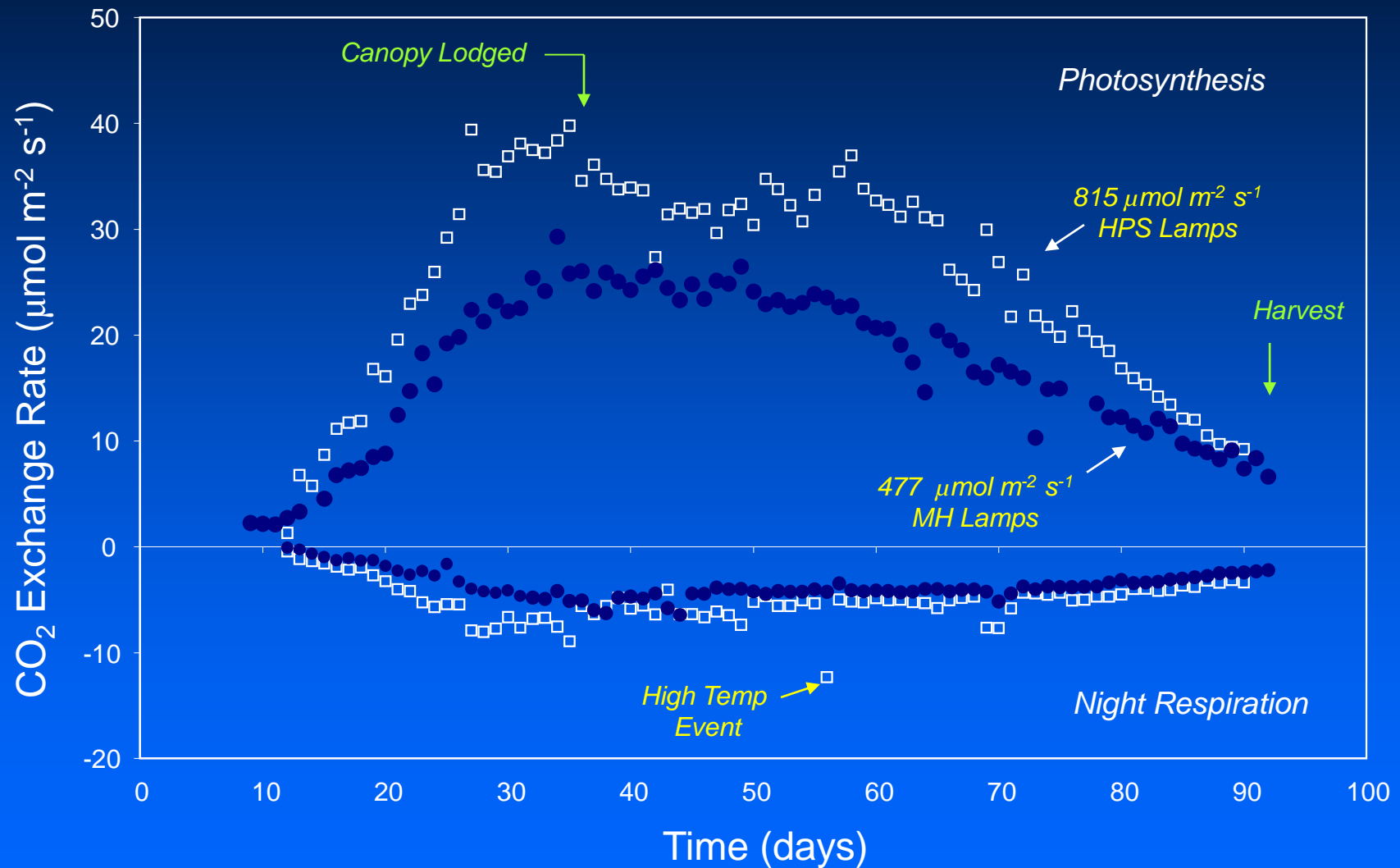
Closed Systems Issues



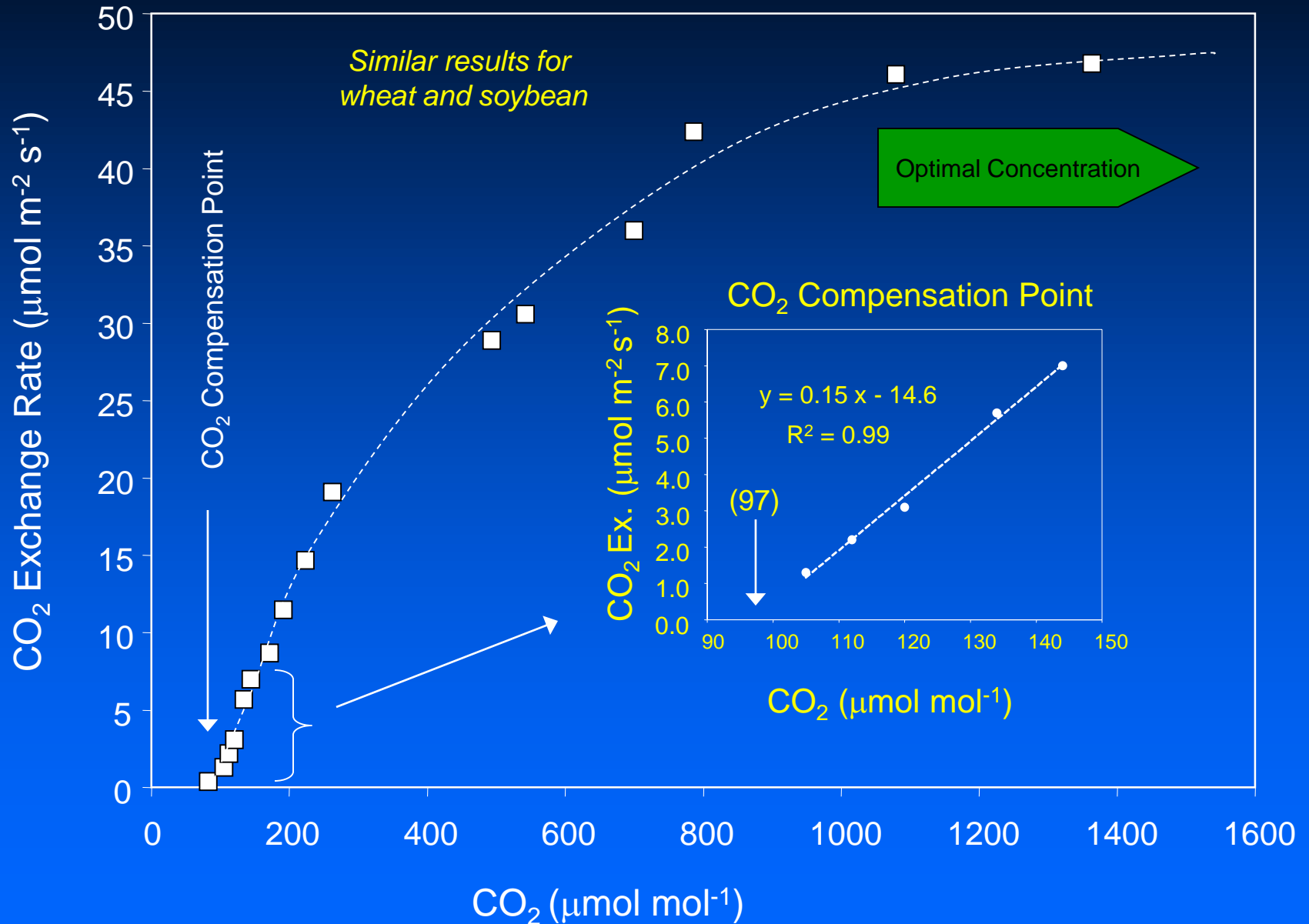
Canopy CO_2 Uptake / O_2 Production (20 m^2 Soybean Stand)



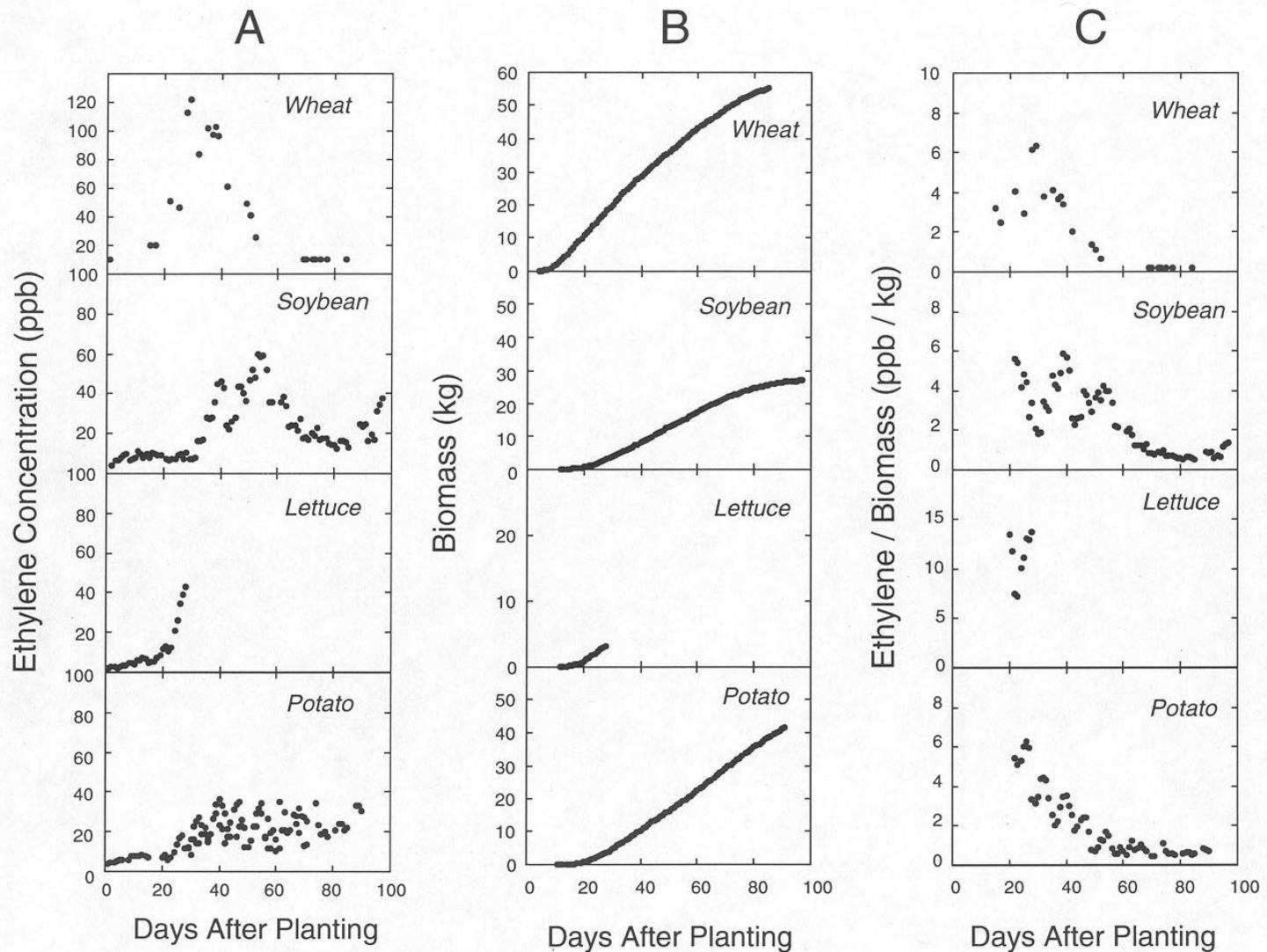
CO₂ Exchange Rates of Soybean Stands



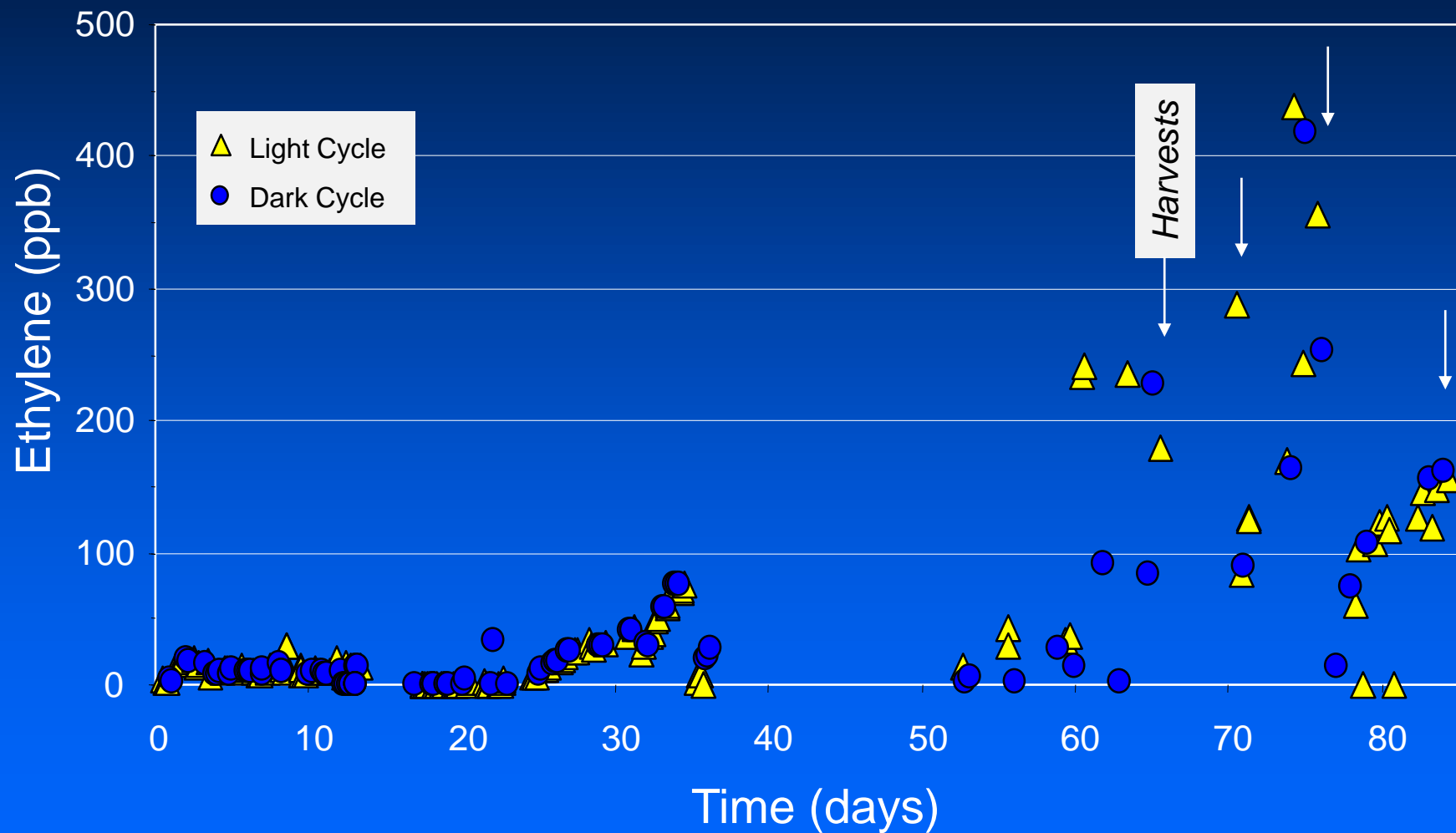
Effect of CO₂ Concentration on Photosynthesis (potato)



Canopy / Stand Ethylene Production



Ethylene Production - Tomato cv. Reimann Philipp



Ethylene in Closed Systems



Epinastic
Wheat Leaves
at ~120 ppb



Epinastic
Potato Leaves
at ~40 ppb

NASA's Biomass Production Chamber (BPC)

An Attempt at Vertical Agriculture !

External View - Back



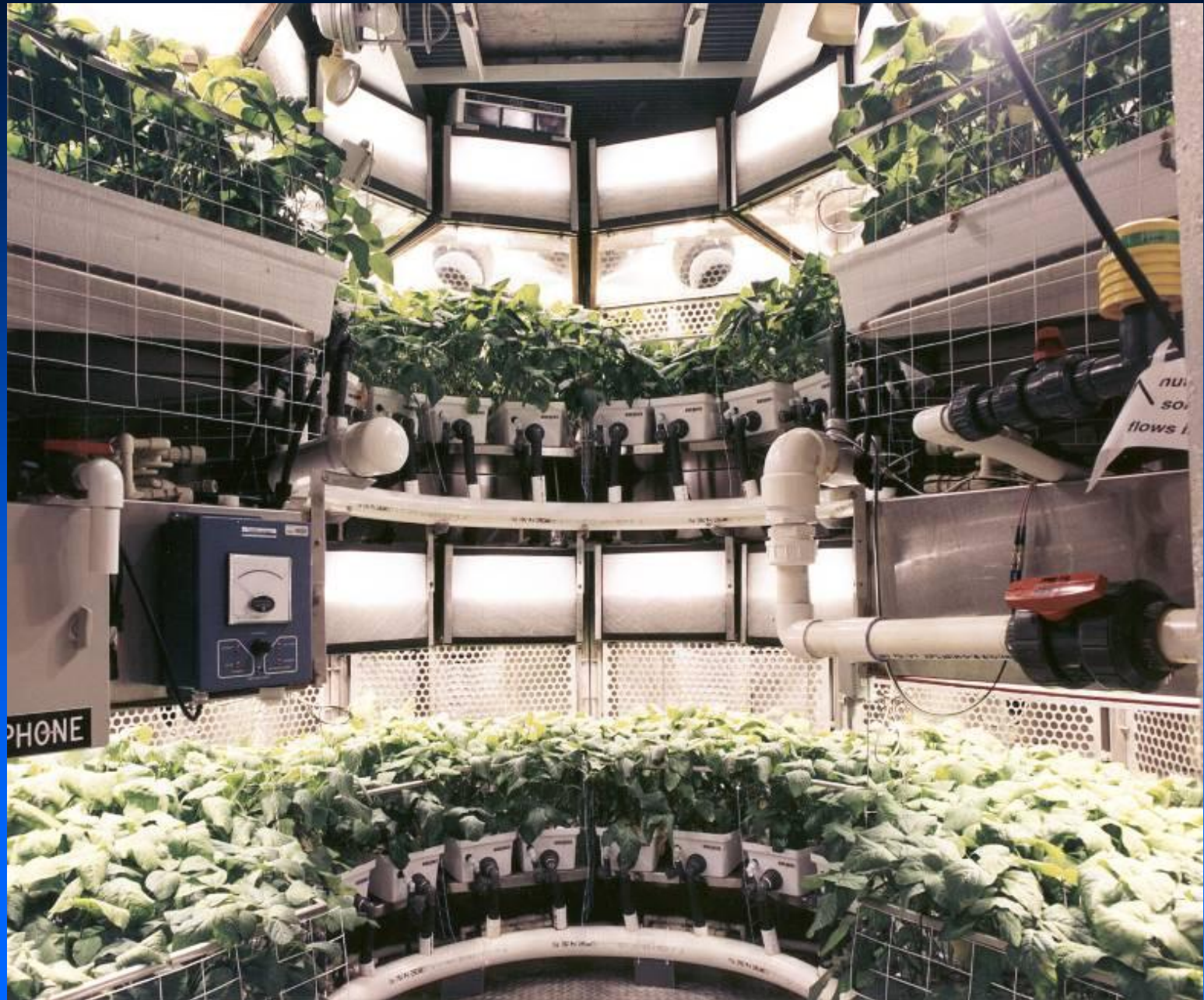
20 m² growing area; 113 m³ vol.; 96 400-W HPS Lamps;
400 m³ min⁻¹ air circulation; two 52-kW chillers

Control Room



Hydroponic System

NASA's Biomass Production Chamber (BPC)

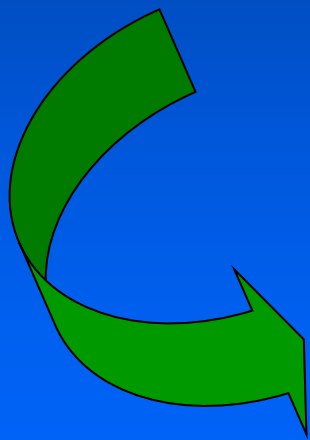


Wheat

(*Triticum aestivum*)



planting



harvest

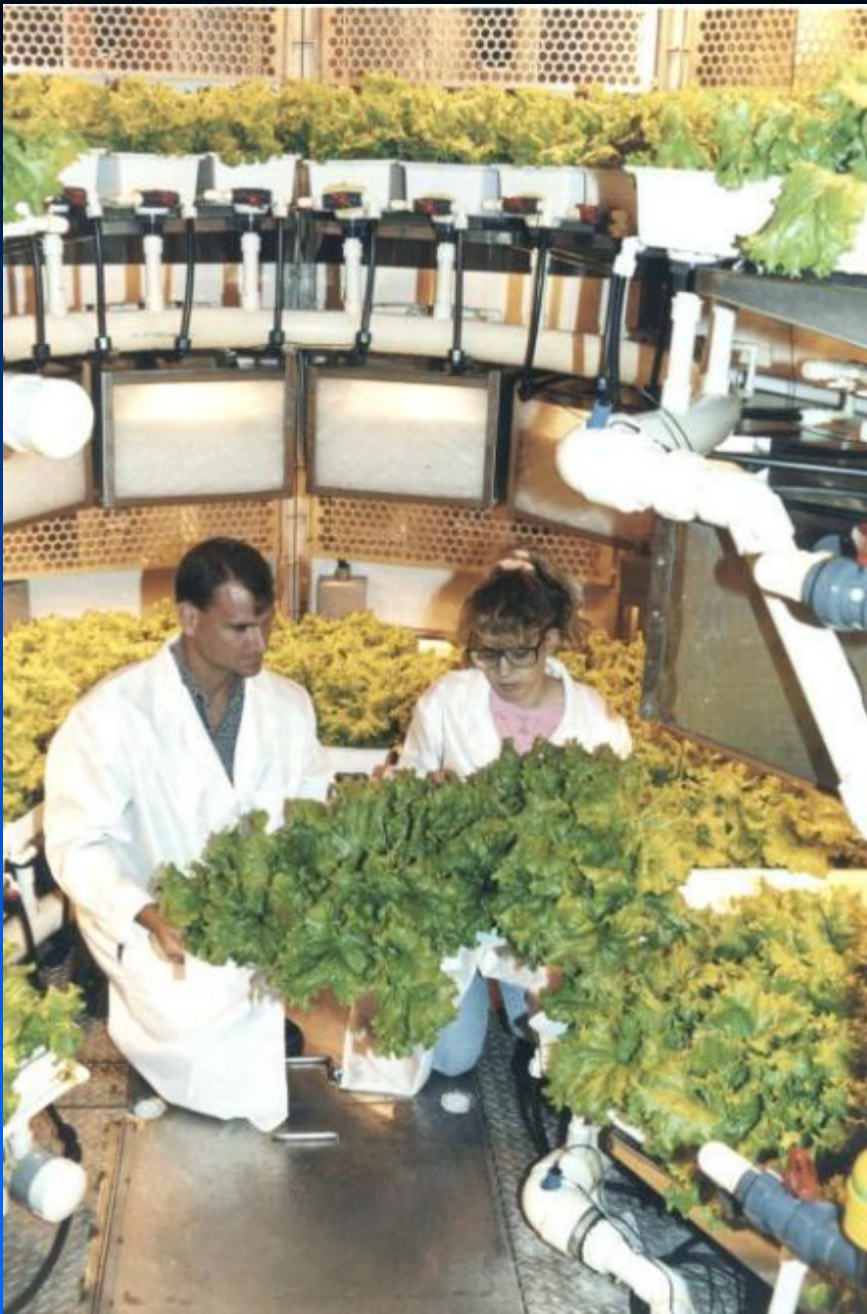
Soybean

(*Glycine max*)



Lettuce

(*Lactuca sativa*)





Potato

(*Solanum tuberosum*)



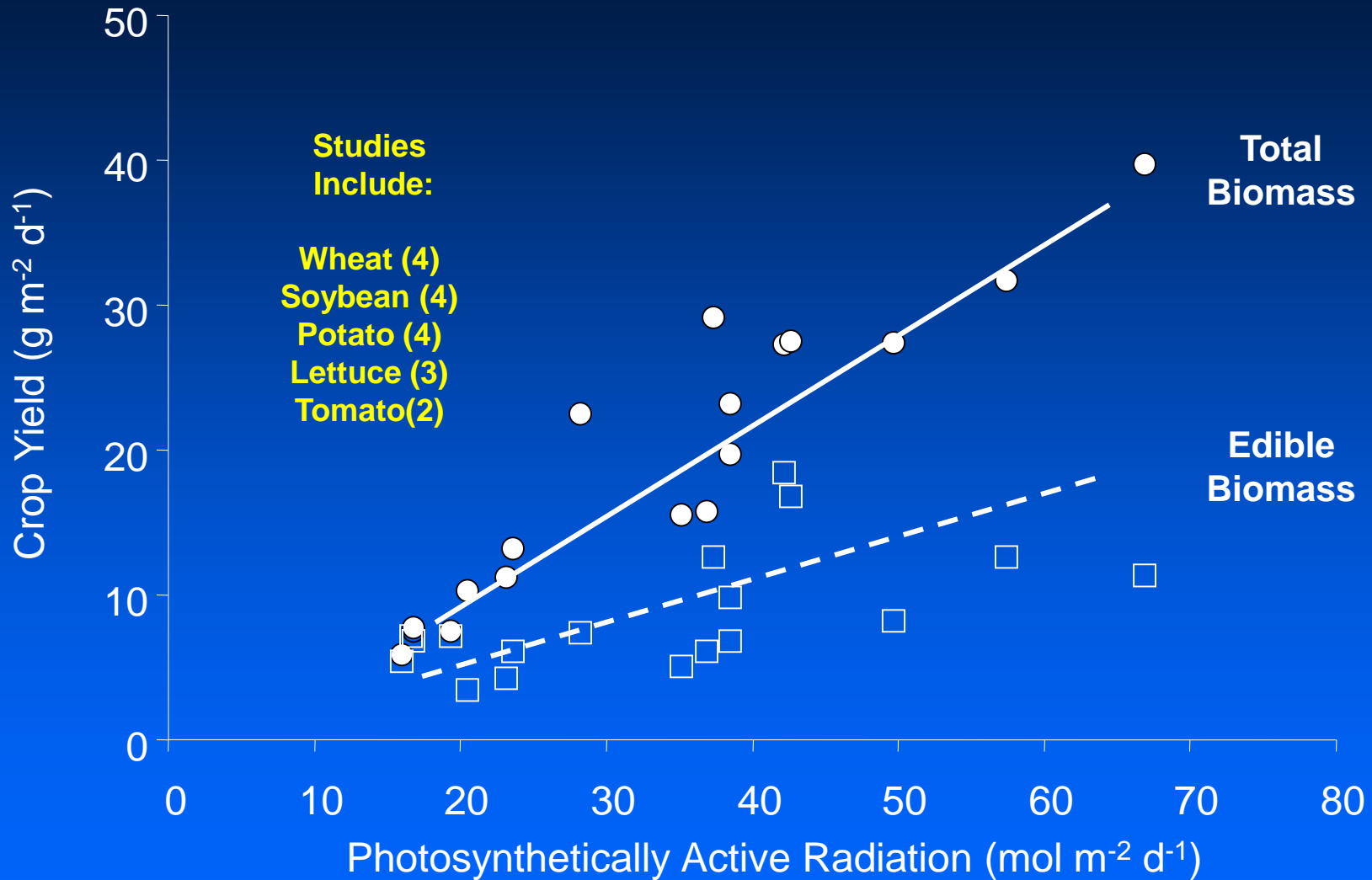
Automation Technologies for CEA



ALSARM Robot in NASA
Biomass Production Chamber



Effect of Light on Crop Yield



Electrical Power for BPC

- 96 400-W HPS lamps with dimming ballasts
 - Two 30 kW blowers ($400 \text{ m}^3 \text{ min}^{-1}$)
 - Two 15-ton (52 kW) chillers for cooling
 - 100 kW water heater for air re-heat
- Not designed for energy efficiency!!

The Importance of Lighting

--Electric Lamp Options

<i>Lamp Type</i>	<i>Conversion* Efficiency</i>	<i>Lamp Life* (hrs)</i>	<i>Spectrum</i>
• Incandescent/Tungsten**	5-10%	2000	Intermd.
• Xenon	5-10%	2000	Broad
• Fluorescent***	20%	5,000-20,000	Broad
• Metal Halide	25%	20,000	Broad
• High Pressure Sodium	30%	25,000	Intermd.
• Low Pressure Sodium	35%	25,000	Narrow
• Microwave Sulfur	35-40%+	?	Broad
• LEDs (red and blue)****	>40%	100,000 ?	Narrow

* *Approximate values.*

** *Tungsten halogen lamps have broader spectrum.*

*** *For VHO lamps; lower power lamps with electronic ballasts last up to ~20,000 hrs.*

**** *State-of-Art Blue and Red LEDs most efficient.*

LED Studies

Red...photosynthesis

Blue...photomorphogenesis

Green...human vision

Some NASA Related References:

Bula et al. 1991. HortSci 26:203-205.

Barta et al. 1992. Adv. Space Res. 12(5):141-149.

Tennessen et al. 1994. Photosyn. Res. 39:85-92.

Goins et al. 1997. J. Exp. Botany 48:1407-1413.

Kim et al. 2004. Ann. Bot. 94:691-697.



Solar Collector / Fiber Optics For Plant Lighting



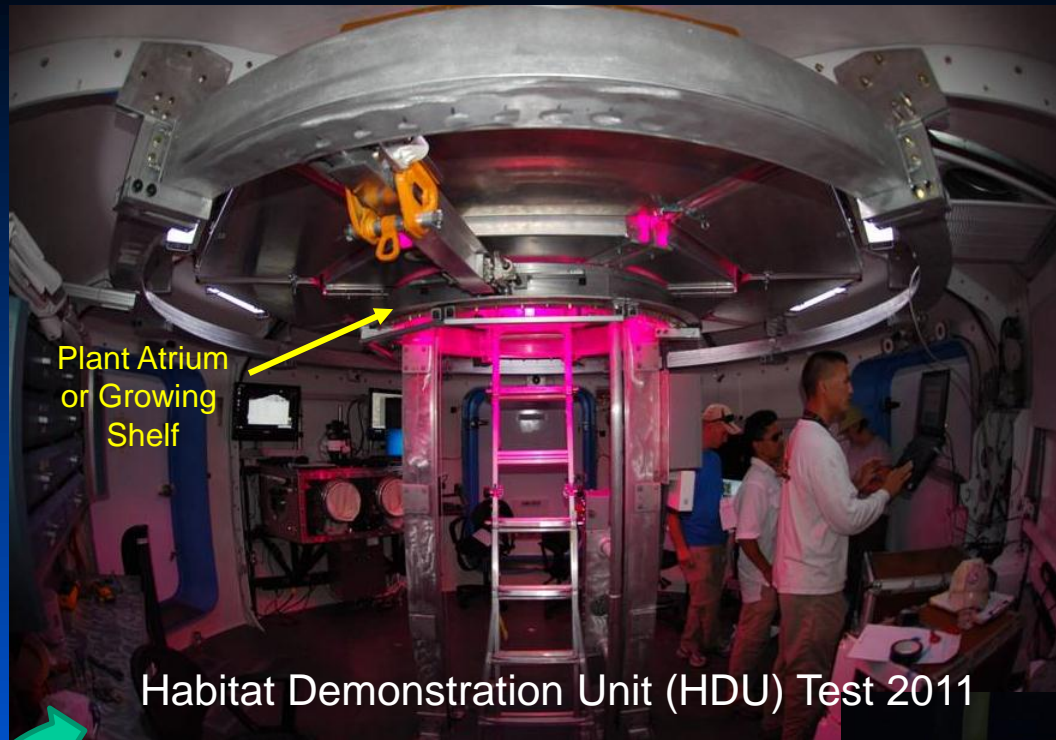
2 m² of collectors on solar tracking drive (SLSL Bldg, NASA KSC)

Up to 400 W light delivered to chamber
(40-50% of incident light)
Takashi Nakamura, Physical Sciences Inc.



Nakamura et al. 2010. Habitation

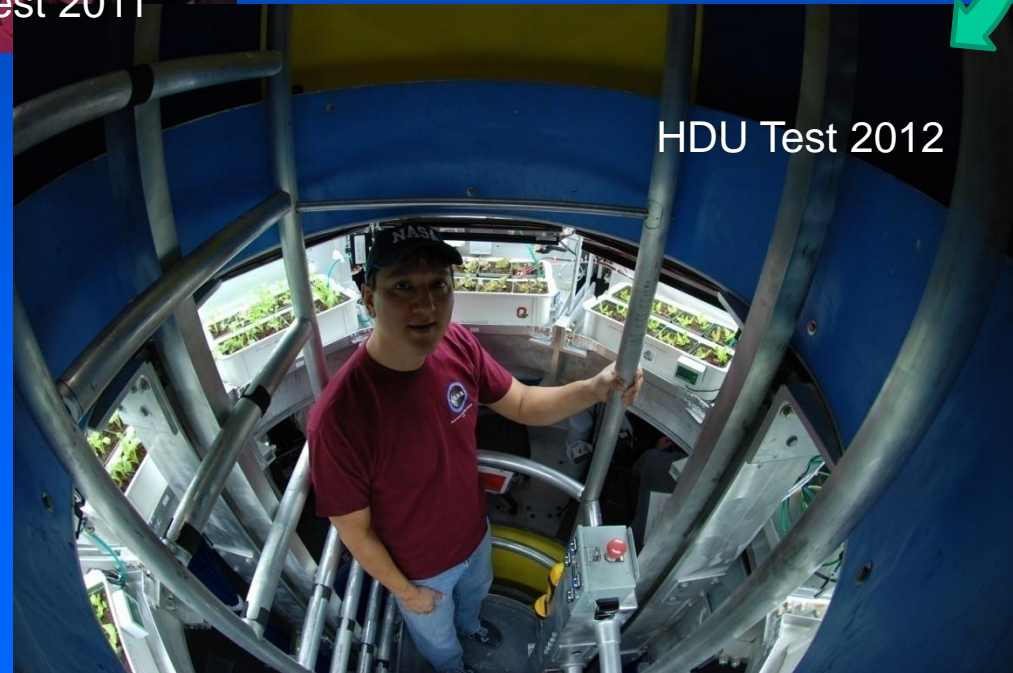
Human Habitats and Crops for Supplemental Food



Habitat Demonstration Unit (HDU) Test 2011

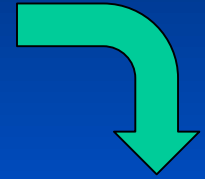
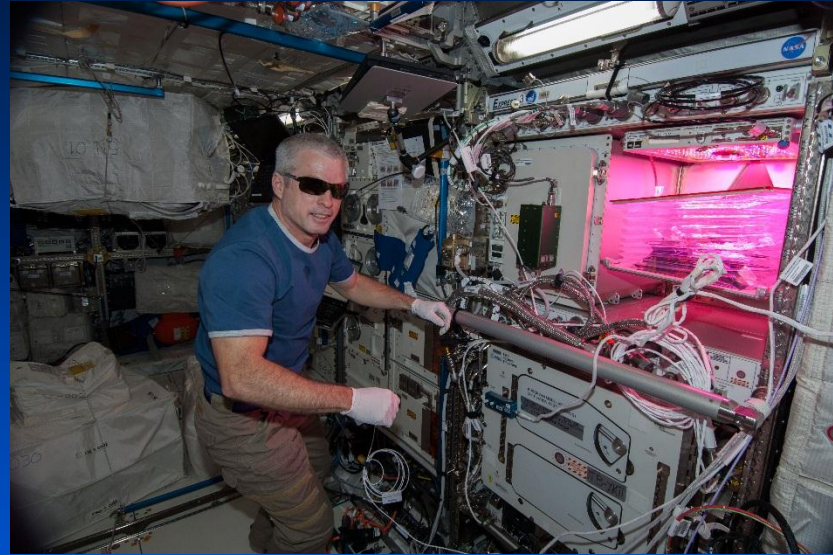
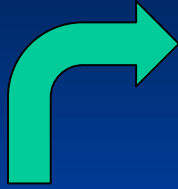


NASA's HDU at Desert Test Site



HDU Test 2012

Plant Growth on the International Space Station—VEGGIE Plant Chamber.



Some Lessons Learned from NASA CEA / Vertical Ag work

- Over half of maintenance / upkeep time dedicated to nutrient system management
 - If condensate water is retrieved, pay attention to elemental content
- Extensive work for optimizing hydroponic solution replenishment recipes
 - We made no attempts to reduce nitrate in tissue
- Consider ability to reach all sections of the growing area; it was not easy for use to inspect the back of our trays; consider shelf-to-shelf height
- Initially we sanitized hydroponic hardware following crops, but later abandoned in favor of thorough cleaning
- Consider innovative means for improving energy efficiency, e.g., if possible use heat from lamps and power supplies for air “re-heat”
- Worker safety—consider sunglasses for working around bright red and blue LEDs

Agriculture in Space

As we explore sustainable living for space, we will learn more about sustainable living on Earth



KSC Advanced Life Support Team, Hangar L, KSC 1994

